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For submission to Water Research as a Full Paper

Photosynthesis in sediments determined at high spatial resolution by the use of microelectrodes

Short running title: Photosynthesis in sediments

By

YOSHIYUKI NAKAMURA 1, HISASHI SATOH 2*, SATOSHI OKABE 1 and YOSHIMASA WATANABE 1

1 Department of Urban and Environmental Engineering, Graduate school of Engineering, Hokkaido University, Sapporo 060-8628, Japan.

2 Department of Environmental and Civil Engineering, Hachinohe Institute of Technology, Hachinohe, Aomori 031-8501, Japan.

Corresponding Author

Hisashi SATOH

Department of Environmental and Civil Engineering, Hachinohe Institute of Technology, 88-1 Ohbiraki, Myo, Hachinohe, Aomori 031-8501, Japan.

Tel.: +81-(0)178-25-8067

Fax.: +81-(0)178-25-0722

E-mail: qsatoh@hi-tech.ac.jp
Abstract

The present study investigated photosynthetic rates and their regulation by light within the upper 5 mm of sediment in a tidal area of Niida River in Hachinohe, Japan. Steady-state concentration profiles of O$_2$, NH$_4^+$, NO$_2^-$, H$_2$S, and pH in the sediment were measured with microelectrodes. Microzonation of O$_2$ respiration, denitrification and SO$_4^{2-}$ reduction was found in the sediment. When light intensities exceeded 1050 µmol photons/m$^2$/s, net photosynthetic activity was detected in the upper 0.5 mm of the microbial mat colonizing on the sediment surface in the tidal area. In contrast, gross photosynthetic activity was detected in the upper 1.0 mm of the microbial mat at 1900 µmol photons/m$^2$/s. As light intensity increased, the net photosynthetic rate and O$_2$ penetration depth increased. The maximal net photosynthetic rate and O$_2$ penetration depth were 6.1 µmol O$_2$/cm$^3$/h and 2.2 mm, respectively, at 1900 µmol photons/m$^2$/s. Net photosynthetic rates in the microbial mat in the tidal area were lower than in the upstream sediment. The analysis of continuous O$_2$ concentration measurements in different layers of the microbial mat during artificial light-dark cycles demonstrated that the photosynthetic activity response to changes in light intensity was extremely fast (a few seconds) and the O$_2$ concentration in the microbial mat became stable within 200 s. The measurement of physical and chemical parameters in river water revealed that the study site was relatively polluted and sunlight intensity significantly fluctuated temporally. These results suggested that the in situ microbial processes occurring in the sediment fluctuated in accordance with periodic fluctuations in sunlight intensity.

Key words

Photosynthesis; Light intensity; River sediment; Tidal area; Microelectrodes

Introduction

Photosynthesis significantly affects carbon and nitrogen cycles in river systems (Falkowski and Raven, 1997b). While the primary photosynthetic microorganisms in the sea are planktonic microalgae, in rivers photosynthetic microorganisms in microbial mats,
which colonize on sediment surface, and in epilithic biofilms that grow on stones, are significant contributors to photosynthetic activity. The microbial mats are compact microbial communities with high specific rates of metabolic processes (Castenholz, 1994). The high rates are due to dense populations of microorganisms and the high availability of organic carbon and nutrients. Photosynthetic microorganisms in the microbial mats act as sources of organic carbon and oxygen (O₂). In addition, the microbial mats receive organic carbon and nutrients from overlying water.

Although the typical thickness of a microbial mat is only a few millimeters, a vertical zonation of the microbial processes can be found in the microbial mat (Jensen et al., 1994; Wieland and Kühl, 2000). The use of microelectrodes has made it possible to study such microzonation of the microbial processes and the tight spatial coupling between them at high spatial resolution. The O₂ respiration process affected nitrification and denitrification in freshwater sediment (Jensen et al., 1994), sulfate (SO₄²⁻) reduction in a hot spring cyanobacterial mat (Wieland and Kühl, 2000), and photosynthesis in hypersaline microbial mats (Grötzschel and de Beer, 2002).

In the river systems, oxygenic photosynthesis, followed by increases in O₂ and organic carbon concentrations, affects the microbial processes in the sediment. Although the thickness of the photosynthetic zone is less than one millimeter due to limited light penetration in the sediment, the specific photosynthetic rate is very high. Microelectrode measurements have revealed the occurrence of oxygenic photosynthesis with high photosynthetic rates in cyanobacterial mats (Wieland and Kühl, 2000; Ramsing et al., 2000) and natural biofilms (Glud et al., 1992). Light (Ramsing et al., 2000), O₂ concentration (Grötzschel and de Beer, 2002) and temperature (Wieland and Kühl, 2000) affect the photosynthetic activity in the cyanobacterial mats. However, very little is known about the microbial processes and the effect of environmental factors in sediment at a river mouth.

Rivers flowing through urban areas receive anthropogenic inputs of organic carbon and nutrients (e.g. nitrogen and phosphorus) from adjacent land (Chen et al., 1999; Sørensen and Revsbech, 1990). At the river mouth, diverse physical and chemical factors (e.g. sunlight, concentrations of organic carbon and nutrients, changes in flow rates and salinity), as well as nutrient retention occur because of tides (Feng et al., 2002). These environmental factors could affect the microbial photosynthesis, O₂ respiration,
nitrification, denitrification, and SO$_4^{2-}$ reduction. Therefore, the microbial processes in the sediment of a tidal area may be spatially and temporally dynamic when compared with other environments.

In the present study, we investigated the effect of light intensity on the net photosynthetic activity of sediment located in a tidal area of the Niida River, Hachinohe, Japan. We further discussed the effect of light intensity on microzonation of the microbial processes. Laboratory measurements of the O$_2$, NH$_4^+$, NO$_2^-$, H$_2$S, and pH concentration profiles, and net and gross photosynthetic rates were performed with microelectrodes. Furthermore, river water quality and environmental conditions of the sediments were determined.

2. Materials and methods

2.1. Sampling

Sediment samples and river water were collected at two points (Point 1 and 2) in the Niida River in Hachinohe, Japan (Fig. 1). The Niida River flows through agricultural areas and a city area in Hachinohe. The population of Hachinohe City is about 245,000. There are several factories of processed marine products around the downstream part of the Niida River. River water samples were collected during April and December 2002. Flow rate at the point 2 ranged from 212 to 2.3 m$^3$/s during the study period and the average was 15 m$^3$/s. Maximal tidal range is 130 cm. The point 1 and 2 are located approximately 1.5 and 8.0 km from the river mouth, respectively. Sediment samples were collected using 4 cm diameter Plexiglas tubes with minimal disturbance. The sediment and river water samples were transferred to the laboratory and were analyzed within 12 h using the methods described below.

2.2. Microelectrode measurements

In the laboratory, steady state concentration profiles of O$_2$, NH$_4^+$, NO$_2^-$, H$_2$S, and pH in the sediments were recorded according to the protocol reported elsewhere (Satoh et al.,
Clark-type microelectrodes for O$_2$ with a tip diameter of approximately 15 µm and a 90 % response time <0.5 s were prepared and calibrated as described by Revsbech (Revsbech, 1989). LIX-type microelectrodes for NH$_4^+$, NO$_2^-$ and pH (de Beer et al., 1997) were constructed, calibrated, and used according to a protocol reported elsewhere (Okabe et al., 1999b). H$_2$S microelectrodes were constructed as described by Revsbech et al. (1983) and were calibrated and used as described elsewhere (Okabe et al., 1999a).

A flow cell reactor (60 (L) × 10 (W) × 5 (H) cm) for microelectrode measurements was constructed using an acrylic board (Fig. 2). The sediment samples were positioned in the reactor, where the surface of the microbial mat colonizing on the sediment surface was aligned with the bottom of the flow cell. 5.0 liter of the medium for microelectrode measurements was fed to the reactor at an average liquid velocity of 2 cm/s. To create a parallel, nonturbulent flow, a metallic net was mounted at the upstream of the reactor. The depth of the water above the microbial mat surface was about 1 cm. For the measurements of O$_2$ concentration profiles in the sediment, raw river water sampled at the sampling points was used as the medium for microelectrode measurements. Light intensity was changed from 10 to 1900 µmol photons/m$^2$/s. When the microprofiles of NH$_4^+$, NO$_2^-$, H$_2$S, and pH in the sediment were measured, a synthetic medium was used to avoid interference with the LIX-type microelectrodes. The synthetic medium consisted of NH$_4$Cl (50 µM), NaNO$_2$ (40 µM), NaNO$_3$ (100 µM), Na$_2$SO$_4$ (2000 µM), Na$_2$HPO$_4$ (3000 µM), MgCl$_2$•6H$_2$O (84 µM), CaCl$_2$ (200 µM), EDTA (270 µM). pH was adjusted to 7.5. Light intensity was adjusted to 10 µmol photons/m$^2$/s. The sediment was then acclimated in the medium at 20°C for at least 30 minutes before measurements to ensure that steady-state profiles were obtained. The microelectrodes were mounted on a motor-driven micromanipulator for accurate positioning and the concentration profiles in the sediment were recorded at intervals of 0.05 to 0.3 mm from the bulk liquid into the sediment (Okabe et al., 1999b). The microbial mat surface was determined by using a dissection microscope (model Stemi 2000; Carl Zeiss). Halogen lamps supplied needed light during the experiments. At least three concentration profiles were measured at different positions in the sediment for each species and set of conditions. When O$_2$ concentrations were measured during artificial light-dark cycles, the sediment was illuminated at 1900 µmol photons/m$^2$/s for 10 minutes and the electrode was introduced into the sediment. The sediment was then shaded and kept in the dark until the O$_2$
concentration became stable. The sediment was then illuminated again at 1900 µmol photons/m²/s and kept in the light until the O₂ concentration became stable. After two light-dark cycles, the electrode was introduced into deeper layers.

2.3. Calculation of metabolic rates

Net specific rates of O₂ production (Pₙₑₙ) or O₂ consumption (Cₙₑₙ) in the sediments were calculated from the mean steady state concentration profiles using Fick’s second law of diffusion including a production or a consumption term:

\[ D_s \left( \frac{d^2 C_s(z)}{dz^2} \right) = C_{net} \text{ or } -P_{net} \]

where \( D_s \) is the effective sediment diffusion coefficient for O₂ and \( C_s(z) \) is the O₂ concentration at depth \( z \). The details of this method were described previously by Lorenzen et al. (1998).

The \( D_s \) was calculated from the free solution molecular diffusion coefficient (\( D_0 \)) for O₂ and the sediment porosity (\( \phi \)) according to Ullman and Aller (1982):

\[ D_s = \phi^2 D_0 \]

The \( D_0 \) for O₂ (2.09×10⁻⁵ cm²/s) at 20°C was found in the literature (Andrussow, 1969).

Porosity and \( D_s \) at relevant depths of the investigated sediments are summarized in Table 2.

Gross photosynthetic rates (\( P_{gross} \)) were determined with same O₂ microelectrodes by the light-dark-shift method (Revsbech and Jørgensen, 1983; Revsbech et al., 1981), in which the decrease in O₂ concentration was determined during a 2 s dark period and the \( P_{gross} \) at each depth could be calculated from the following equation:

\[ P_{gross} = -\frac{dC_s(t)}{dt} \]

where \( dC_s(t)/dt \) is the rate of O₂ disappearance during 2 s after darkening. Theory of this method was described elsewhere (Revsbech et al., 1981). A short summary is given here. A steady state O₂ profile in the sediment will be approached after a long period of illumination.

At steady state, the photosynthetic O₂ production in any layer will balance the combined losses due to respiration and to diffusion of O₂ away from that layer (calculated negative if there is a net diffusion to the layer). When illumination is suddenly stopped, diffusion and respiration are initially unchanged, so that the O₂ concentration in the layer will decrease at a rate equal to the former photosynthetic rate. Furthermore, specific O₂ respiration rates
(R_{O2}) were calculated from these rates by subtracting the P_{net} from the P_{gross} for each layer of the sediment.

2.4. Analytical methods

Chemical Oxygen Demand (COD), using KMnO_4 as an oxidant, Biochemical Oxygen Demand (BOD) and Dissolved Organic Carbon (DOC) were analyzed according to the Standard Methods (APHA, 1998). The NH_4^+ and NO_2^- concentrations were determined colorimetrically. The NO_3^- and SO_4^{2-} concentration was determined using an ion chromatograph (HIC-6A; Shimadzu) equipped with a Shim-pack IC-A1 column. The samples for NH_4^+, NO_2^-, NO_3^- and SO_4^{2-} were filtered with 0.2 µm membrane filters before analysis. Porosity of the sediment was analyzed according to the methods of Murdroch and Azcue (1995). Ignition loss was measured from the loss of volatile matter upon ignition at 600°C for 2 h. Total iron (T-Fe) concentration in the sediment was analyzed using an atomic adsorption spectrophotometer (AA-670; Shimadzu) after a proper sample pretreatment (APHA, 1998). Light intensity was measured by a quantum meter (Fujiwara Scientific Company), which senses only in the 400 to 700 nm region. All measurements were made above the water surface. Salinity was measured using a salinometer. The O_2 concentration and pH were determined using an O_2 electrode and a pH electrode, respectively.

3. Results and discussion

3.1. Physical and chemical parameters in river water and sediments at the study sites

Physical and chemical parameters (average ± standard deviation) of the river water (n=57) at the point 1 are shown in Table 1. The river water quality at the point 1 was relatively polluted while BOD was low and the NH_4^+ concentration was below the detection limit at the point 2 (data not shown). The average NO_3^- concentration was 127 µM at the point 1. SO_4^{2-} concentrations and salinity fluctuated, indicating that the point 1 was located in a tidal area. The sediment located at the point 1 was exposed to atmosphere for several hours during the spring tide. The sediment at the point 1 consisted of sand and the sediment
at the point 2 consisted of silt (Murdroch and Azcue, 1995). A ca. 1 mm thick brownish microbial mat colonized on the sediment surface at the point 1. A black layer underlay the microbial mat, indicating the precipitation of iron sulfide (FeS) in the sediment. Average values of porosity and Ds for O₂, which was calculated from the molecular diffusion coefficient for O₂ in water and the average value of porosity, at relevant depths of the investigated sediments are summarized in Table 2. The average value of porosity (n=6) slightly decreased with depth. Ignition loss in the upper 5 mm of the sediments at the point 1 and point 2 (n=6) was 4.8 ± 0.5 % and 3.4 ± 0.5 %, respectively. Benthic animals (Tylorrhynchus heterochaetus) were found at a density of about 2,000 individuals/m² in the sediment at the point 1. The average concentration profile of T-Fe in the sediment at the point 1 (n=6) is shown in Fig. 3. The average T-Fe concentration was 21 mg/g dry weight in the microbial mat. The T-Fe concentration slightly increased with depth and the maximum concentration was 25 ± 12 mg/g at a depth of 4-5 mm.

The diurnal cycle of sunlight intensity on the surface of the sediment at the point 1 in June 2003 is shown in Fig. 4. The light intensity increased as the sun rose and reached its maximum (1920 µmol photons/m²/s) just before noon on sunny days. The light intensity then gradually decreased during the afternoon. The light intensities on cloudy days showed the same trend, but were less than half of the light intensities on sunny days. Even on sunny days, when clouds shaded the sediment surface, the light intensity decreased to the level of cloudy days within a few seconds.

3.2. Concentration profiles in sediments

Representative 2-D contour plots of O₂ in the sediment at the point 1 at 10 µmol photons/m²/s, constructed from 11 vertical O₂ profiles, are shown in Fig. 5. The sediment sample was collected on 6 June 2001. The O₂ concentration in the bulk liquid was ca. 130 µM. O₂ decreased in the diffusive boundary layer above the microbial mat. The O₂ concentrations at the microbial mat surface were almost the same (90 µM) at all measuring points. The contour lines of 10, 30 and 60 µM of O₂ followed the microbial mat surface.

Mean steady-state concentration profiles of O₂, NH₄⁺, NO₂⁻, H₂S, and pH in the sediment at the point 1 at 10 µmol photons/m²/s are shown in Fig. 6. The sediment sample
was collected on 23 January 2002. O$_2$ penetrated 1.3 mm into the microbial mat. The NH$_4^+$ produced in deeper parts of the sediment diffused toward the microbial mat and was consumed in the microbial mat. NO$_2^-$ concentration decreased in the upper parts of the oxic zone due to nitrification. NO$_2^-$ concentration profile showed a peak of ca.150 µM at a depth of 1.0 mm. Decreased NO$_2^-$ concentrations in the lower parts of the oxic zone and anoxic sediment were probably due to denitrification. H$_2$S was detected in the sediment below a depth of 3.0 mm, indicating SO$_4^{2-}$ reduction occurred in this zone. These results clearly indicate the microzonation of O$_2$ respiration, denitrification and SO$_4^{2-}$ reduction in the upper 5 mm of the microbial mat and sediment. Decrease in H$_2$S concentration at a depth of 2.7 mm could be explained by H$_2$S oxidation by NO$_2^-$ and NO$_3^-$ and H$_2$S fixation with Fe. The abundance of T-Fe in the deeper parts of the sediment (Fig. 3) reflected this result.

3.3. Effect of light intensity on O$_2$ concentration profiles and photosynthesis in the sediments

The effects of oxygenic photosynthesis on O$_2$ concentration in the sediments at the point 1 were investigated because O$_2$ concentration affected the microzonation of O$_2$ respiration, denitrification and SO$_4^{2-}$ reduction (Jensen et al., 1994; Wieland and Kühl, 2000). Mean steady-state O$_2$ concentration profiles measured at five different light intensities and calculated net rates of O$_2$ production ($P_{net}$) and O$_2$ consumption ($C_{net}$) in the sediment are shown in Fig. 7A to 7E. The sediment sample was collected on 1 July 2003. The photosynthetic activities were detected in the upper 0.5 mm of the microbial mat when light intensities were more than 1050 µmol photons/m$^2$/s. As light intensity increased, the $P_{net}$ in the microbial mat increased, resulting in increases in O$_2$ penetration depth and maximal O$_2$ concentration in the sediment. The maximal O$_2$ concentration in the microbial mat increased to 240 µM at a depth of 0.2 mm at 1900 µmol photons/m$^2$/s, which was 1.4 times higher than that of the bulk liquid. In this layer the $P_{net}$ was 6.1 µmol O$_2$/cm$^3$/h. The average O$_2$ penetration depth at 1900 µmol photons/m$^2$/s was 2.2 mm, which was about three times deeper than in the sediment at 10 µmol photons/m$^2$/s (Fig. 7A). These results indicate that in nature, the O$_2$ penetration depth in the sediment could change from ca. 0.7 mm to ca. 2.2 mm in accordance with fluctuations in sunlight intensity (Fig. 4).
Increase in O$_2$ penetration depth results in higher redox potential in the upper parts of the sediment (Jørgensen et al., 1979) and a shift in the zones of anoxic microbial processes (i.e. denitrification and SO$_4^{2-}$ reduction) to the deeper layers of the sediment (Jensen et al., 1994; Wieland and Kühl, 2000). In this study, microzonation of O$_2$ respiration, denitrification and SO$_4^{2-}$ reduction was found in the sediment (Fig. 6). Consequently, the locations of the zones of anoxic microbial processes should fluctuate in accordance with a diurnal cycle of sunlight intensity. In the deeper parts of the sediment, the metabolic rates were low because biodegradable organic carbon and nutrients were usually limited due to the long diffusional distance from overlying water, although limited nutrients were supplied from below. Therefore, denitrification and SO$_4^{2-}$ reduction rates might be higher during the night as compared with in the daytime. These results indicate that fluctuations in sunlight intensity might indirectly affect the carbon and nitrogen cycles in the sediment. However, many physical and chemical factors (e.g. vertical hydraulic flow within pores of the sediment induced by tide, water turbulence on the sediment surface, and fluctuations in organic carbon and nutrient concentrations in river water) affect O$_2$ distribution in the sediment in nature. Consequently, our results present the mechanism of change in O$_2$ distribution in the sediment by light rather than O$_2$ concentration profiles in the sediment in nature.

C$_{\text{net}}$ was high just below the net O$_2$ production zone. With increasing light intensity, the maximal C$_{\text{net}}$ increased; the C$_{\text{net}}$s were 0.7, 1.3 and 1.8 µmol O$_2$/cm$^3$/h at 1050, 1550 and 1900 µmol photons/m$^2$/s, respectively. This was probably due to increasing concentrations of O$_2$ and organic carbon provided from photosynthetic zone in this zone.

The profiles of the average gross photosynthetic rate ($P_{\text{gross}}$) and O$_2$ respiration rate ($R_{O2}$) in the sediment at the point 1 at 1900 µmol photons/m$^2$/s are shown in Fig. 8. The sediment sample was collected on 16 July 2003. The $R_{O2}$ was calculated by subtracting the $P_{\text{net}}$ shown in Fig. 7E from the $P_{\text{gross}}$. The $P_{\text{gross}}$ peaked at a depth of 0.2 mm with the rate of 8.6 µmol O$_2$/cm$^3$/h and then decreased gradually with depth. Gross photosynthesis occurred from the surface to a depth of 1.0 mm, while the net photosynthesis was detected in the upper 0.5 mm of the microbial mat (Fig. 7E). This indicates that the photic zone ranged from the surface to a depth of 1.0 mm. The $R_{O2}$s in the photic zone were below 2.9 µmol O$_2$/cm$^3$/h. These values were comparable with the C$_{\text{net}}$s in the sediment at 10 µmol photons/m$^2$/s (Fig.
Representative steady-state O\textsubscript{2} concentration profiles measured at five different light intensities and P\textsubscript{net} and C\textsubscript{net} in the sediment located at the point 2 are shown in Fig. 9A to 9E. The sediment sample was collected on 9 September 2001. The P\textsubscript{net} in the sediment at the point 2 was higher than in the sediment at the point 1 (Fig. 7). In the sediment photosynthesis occurred even at 100 µmol photons/m\textsuperscript{2}/s (Fig. 9B). The P\textsubscript{net} (6.6 µmol O\textsubscript{2}/cm\textsuperscript{3}/h) at 100 µmol photons/m\textsuperscript{2}/s was highest at a depth of 0.1 mm in the sediment. This value was higher than in the sediment at the point 1 at 1900 µmol photons/m\textsuperscript{2}/s (Fig. 7E). With increasing light intensity, the maximal P\textsubscript{net} in the sediment at the point 2 increased. The P\textsubscript{net} increased to 13.2 µmol O\textsubscript{2}/cm\textsuperscript{3}/h at a depth of 0.1 mm at 1250 µmol photons/m\textsuperscript{2}/s. The difference in the photosynthetic rates between these two types of sediment may be attributed to difference in photosynthetic microorganisms between the sampling sites, although the photosynthetic microorganisms in the sediments were not investigated.

Continuous readings of O\textsubscript{2} concentrations in different layers of the sediment at the point 1 during artificial light-dark cycles are shown in Fig. 10A to 10D. The sediment sample was collected on 1 August 2003. At depths of 0.2, 0.4 and 0.6 mm, the O\textsubscript{2} concentration immediately decreased after darkening (0 s) and became stable within 200 s. Thereafter, when the sediment was illuminated again, the O\textsubscript{2} concentration increased immediately at depths of 0.2 and 0.4 mm, however, a small lag (a few seconds) occurred before O\textsubscript{2} started to increase at a depth of 0.6 mm (Fig. 10D). The steady-state O\textsubscript{2} concentration in the light gradually decreased as the light-dark cycle progressed. This was significant in the deeper layers, that is, in the later measurements. The possible explanations for a decrease in the maximal O\textsubscript{2} concentration might be an inherent circadian rhythm of the photosynthetic microorganisms (Falkowski and Raven, 1997a), migration of photosynthetic microorganisms into deeper layers of the sediment (Ramsing \textit{et al.}, 2000), and/or increased photorespiration (Glud \textit{et al.}, 1992).

Conclusions

Photosynthetic activities in the sediment in the tidal area of Niida River in Hachinohe, Japan, were determined at high spatial resolution by microelectrode technique.
Photosynthesis occurred in the upper 0.5 mm of the sediment. Microelectrode measurements revealed that a vertical microzonation of O$_2$ respiration, denitrification and SO$_4^{2-}$ reduction was found in the upper 5 mm of the sediment. As light intensity increased, the net photosynthetic rate and O$_2$ penetration depth in the sediment increased. Consequently, the location and activities of anoxic microbial processes occurring in the sediment could fluctuate in accordance with periodic fluctuations in sunlight intensity.
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sediments measured by oxygen microprofile, H¹⁴CO₃⁻ fixation, and oxygen exchanged


List of Figures

Table 1. Summary of physical and chemical parameters of river water at the point 1 in the Niida River, Hachinohe, Japan. Values indicate average ± standard deviations.

Table 2. Porosity and the effective sediment diffusion coefficient (Ds) for O$_2$ at relevant depths of the investigated sediments. Values indicate average ± standard deviations.

Fig. 1. Map showing the sampling locations (point 1 and 2) in the Niida River.

Fig.2. Schematic presentation of a flow cell reactor setup.

Fig. 3. Mean concentration profile of T-Fe in the sediment at the point 1. Error bars represent standard deviations of measurements. Microbial mat and sediment are indicated by the gray area and dotted area, respectively.

Fig. 4. Diurnal cycle of sunlight intensity at the point 1. The light intensities on sunny days and cloudy days are indicated by open circles and closed circles, respectively. The time span from sunset to sunrise is indicated by gray shading. The measurements were conducted in June 2003.

Fig. 5. Representative 2-D contour plots of O$_2$ concentrations in a vertical cross section of the sediment at the point 1. The O$_2$ concentrations were measured at light intensities of 10 $\mu$mol photons/m$^2$/s. Numbers in the right margin indicate O$_2$ concentrations. The microbial mat surface, determined by microscopic observation, is indicated by a line. Microbial mat and sediment are indicated by the gray area and dotted area, respectively.

Fig. 6. Mean steady-state concentration profiles of O$_2$, NH$_4^+$, NO$_2^-$, H$_2$S, and pH in the sediment at the point 1. The O$_2$ concentrations were measured at light intensities of 10 $\mu$mol photons/m$^2$/s. Error bars represent standard deviations of measurements. The microbial mat surface is at a depth of 0 $\mu$m. Microbial mat and sediment are indicated by
the gray area and dotted area, respectively.

**Fig. 7.** Mean steady-state $O_2$ concentration profiles (open circles) and calculated net rates of $O_2$ production and consumption (bars) in the sediment at the point 1. The $O_2$ concentrations were measured at light intensities of 10 (A), 400 (B), 1050 (C), 1550 (D), and 1900 (E) µmol photons/m²/s. Error bars represent standard deviations of measurements. Positive and negative values indicate $O_2$ production and $O_2$ consumption rates, respectively. The microbial mat surface is at a depth of 0 µm. Microbial mat and sediment are indicated by the gray area and dotted area, respectively.

**Fig. 8.** Profiles of average gross photosynthetic rate (filled circles) and calculated $O_2$ respiration rate (open circles) in the sediment at the point 1 at 1900 µmol photons/m²/s. Error bars represent standard deviations of measurements. Positive and negative values indicate $O_2$ production and $O_2$ respiration rates, respectively. The microbial mat surface is at a depth of 0 µm. Microbial mat and sediment are indicated by the gray area and dotted area, respectively.

**Fig. 9.** Representative steady-state $O_2$ concentration profiles (open circles) and calculated net rates of $O_2$ production and consumption (bars) in the sediment at the point 2. The $O_2$ concentrations were measured at light intensities of 10 (A), 100 (B), 400 (C), 730 (D), and 1250 (E) µmol photons/m²/s. Positive and negative values indicate $O_2$ production and $O_2$ consumption rates, respectively. The microbial mat surface is at a depth of 0 µm. Microbial mat and sediment are indicated by the gray area and dotted area, respectively.

**Fig. 10.** The time course of $O_2$ concentration at a depth of 0.2 (A), 0.4 (B) and 0.6 (C) mm in the sediment at the point 1. The panel D shows a close-up view of the panel C in the elapsed time from 7130 to 7170 s. The sediment was artificially illuminated and shaded repeatedly. The shaded areas indicate periods of dark incubation. Note the expanded time scale in the panel A, B and D.
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<th>COD (mg/L)</th>
<th>BOD (mg/L)</th>
<th>DOC (mg/L)</th>
<th>NH₄⁺ (µM)</th>
<th>NO₂⁻ (µM)</th>
<th>NO₃⁻ (µM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.8 ± 8.2</td>
<td>4.4 ± 2.0</td>
<td>11.2 ± 7.3</td>
<td>44 ± 39</td>
<td>1 ± 5</td>
<td>127 ± 168</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>O₂ (µM)</th>
<th>SO₄²⁻ (µM)</th>
<th>Salinity (%)</th>
<th>Temperature (°C)</th>
<th>pH (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>190 ± 40</td>
<td>3400 ± 3500</td>
<td>0.23 ± 0.24</td>
<td>17.4 ± 3.9</td>
<td>7.3 ± 0.8</td>
</tr>
</tbody>
</table>

Table 1
Photosynthesis in sediment determined at high spatial resolution by the use of microelectrodes
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<table>
<thead>
<tr>
<th>Sample</th>
<th>Distance from the surface (mm)</th>
<th>Porosity (−)</th>
<th>Ds (10⁻⁵ cm²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point 1</td>
<td>0-5</td>
<td>0.82 ± 0.09</td>
<td>1.40</td>
</tr>
<tr>
<td></td>
<td>5-10</td>
<td>0.82 ± 0.07</td>
<td>1.41</td>
</tr>
<tr>
<td></td>
<td>10-15</td>
<td>0.79 ± 0.06</td>
<td>1.31</td>
</tr>
<tr>
<td></td>
<td>15-20</td>
<td>0.79 ± 0.08</td>
<td>1.30</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>0.78 ± 0.07</td>
<td>1.27</td>
</tr>
<tr>
<td></td>
<td>30-40</td>
<td>0.76 ± 0.09</td>
<td>1.20</td>
</tr>
<tr>
<td></td>
<td>40-50</td>
<td>0.77 ± 0.11</td>
<td>1.23</td>
</tr>
<tr>
<td></td>
<td>50-60</td>
<td>0.75 ± 0.11</td>
<td>1.18</td>
</tr>
<tr>
<td>Point 2</td>
<td>0-50</td>
<td>0.61 ± 0.04</td>
<td>0.78</td>
</tr>
</tbody>
</table>

Table 2
Photosynthesis in sediment determined at high spatial resolution by the use of microelectrodes
Yoshiyuki Nakamura et al.
Fig. 1
Photosynthesis in sediments determined at high spatial resolution by the use of microelectrodes
Yoshiyuki Nakamura et al.
Fig. 2
Photosynthesis in sediments determined at high spatial resolution by the use of microelectrodes. Yoshiyuki Nakamura et al.
Fig. 3
Photosynthesis in sediment determined at high spatial resolution by the use of microelectrodes
Yoshiyuki Nakamura et al.
Fig.*
Macroscale.
Yoshiyuki Nakamura et al.
Fig. 4
Photosynthesis in sediment determined at high spatial resolution by the use of microelectrodes
Yoshiyuki Nakamura et al.
Fig. 5
Photosynthesis in sediment determined at high spatial resolution by the use of microelectrodes
Yoshiyuki Nakamura et al.
Fig. 6
Photosynthesis in sediment determined at high spatial resolution by the use of microelectrodes
Yoshiyuki Nakamura et al.
Fig. 7
Photosynthesis in sediment determined at high spatial resolution by the use of microelectrodes
Yoshiyuki Nakamura et al.
Fig.*

Macroscale.

Yoshiyuki Nakamura et al.
Fig. 8
Photosynthesis in sediment determined at high spatial resolution by the use of microelectrodes
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Fig.*
Mcroscale.
Yoshiyuki Nakamura et al.
Fig. 9
Photosynthesis in sediment determined at high spatial resolution by the use of microelectrodes
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Fig.*
Macroscale.
Yoshiyuki Nakamura et al.
Fig. 10
Photosynthesis in sediment determined at high spatial resolution by the use of microelectrodes
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